MEASUREMENTS OF SURFACE PLASMA EVOLUTION FROM A Z CURRENT-RETURN STRUCTURE FIELDED ON GAMBLE II[*]

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Abstract

Plasmas generated near conductor surfaces with ~ MA/mm^2 current density are diagnosed on Gamble II (1 MA/100 ns) for conditions relevant to a Z (20 MA/100 ns) wire-array z-pinch configuration. Plasma density greater than 10^{14} cm^{-3} is detected 1 mm from the conductor beginning 100 ns after the start of the current. The plasma expands with 2 cm/μs velocity. High-density (10^{17}-10^{18} cm^{-3}) plasma migrates more slowly (~ 0.5 cm/μs) away from the ribs. Three different rib cross sections appear to have little influence on the shape of the expanding plasma or its initial density time-history. Plasma expansion from gold-coated ribs appears to be about the same as from stainless ribs if the stainless ribs are cleaned in acetone prior to the shot. Stainless ribs that are not cleaned appear to generate plasma sooner. Implications for Z experiments and future experiments are discussed.

I. MOTIVATION AND EXPERIMENT

The Z generator[1] produces a 20 MA/100 ns current that passes through a cylindrical wire array and a surrounding return conductor. The return conductor is often a thin-walled cylinder with slots to allow diagnostic access to the pinch (Fig. 1a). The current density in the return structure ribs is greatest at the edges, exceeding 1 MA/mm^2, possibly leading to plasma generation that could result in power flow problems and x-ray attenuation.

An experiment was performed on Gamble II using its 1 MA/100ns current pulse to replicate the conditions near one such Z slot. This allows investigation of the plasmas produced at similar current density, but without the radiation environment produced by the pinch.

The return conductor geometry for Z shot 51 (Z51) is depicted in Fig 1a. The circle represents the initial position of the wire array. The shaded arcs are the ribs that conduct the return current. The dimensions of the ribs and slot are shown in Fig. 1b. The axial length of the slots is 2 cm.

A strip-line mockup of one slot used to diagnose plasmas on Gamble II is depicted in Fig. 1c. The slot width, length and conductor thickness were retained, but the rib width (in the azimuthal dimension) was reduced so the current density would approximate that on Z. The ribs are connected to a planar return conductor 5 mm away.

Calculated current distributions are compared in Fig. 2 for Z51 and the three rib cross sections tested on Gamble II. (Only the upper conductor of the pair used on Gamble II is shown in the figure.) The current densities were calculated using f = 5 MHz and the room temperature resistivity of stainless steel, so they do not precisely represent the transient response or heating effects. The three rib cross sections are denoted "no bevel" (Fig 2b), "bevel in" (Fig. 2c) and "bevel out" (Fig. 2d). The maximum current density for Z51 conditions (2 MA/rib) is 1.7 MA/mm^2 at the inside corner of the rib. The maximum current density for the Gamble II conditions
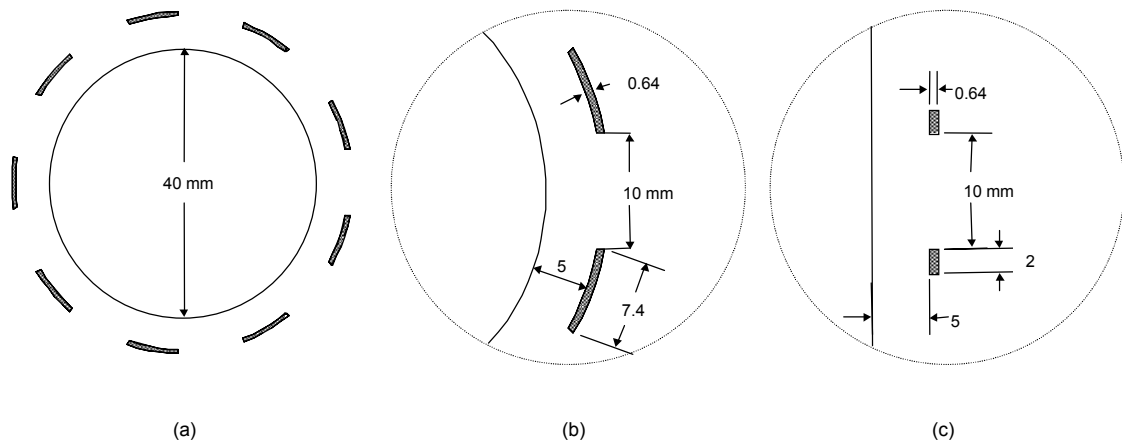

Figure 1. (a) Cross section of a 40-mm diameter wire array with a cylindrical return conductor with nine slots. (b) Close-up of one slot with dimensions in mm. (c) Stripline arrangement of one slot on Gamble II for plasma measurements.

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14. ABSTRACT
Plasmas generated near conductor surfaces with ~ MA/mm2 current density are diagnosed on Gamble II (1 MA/100 ns) for conditions relevant to a Z (20 MA/100 ns) wire-array z-pinch configuration. Plasma density greater than 1014 cm-3 is detected 1 mm from the conductor beginning 100 ns after the start of the current. The plasma expands with 2 cm/İs velocity. High-density (1017-1018 cm-3) plasma migrates more slowly (~ 0.5 cm/İs) away from the ribs. Three different rib cross sections appear to have little influence on the shape of the expanding plasma or its initial density time-history. Plasma expansion from gold-coated ribs appears to be about the same as from stainless ribs if the stainless ribs are cleaned in acetone prior to the shot. Stainless ribs that are not cleaned appear to generate plasma sooner. Implications for Z experiments and future experiments are discussed.

15. SUBJECT TERMS

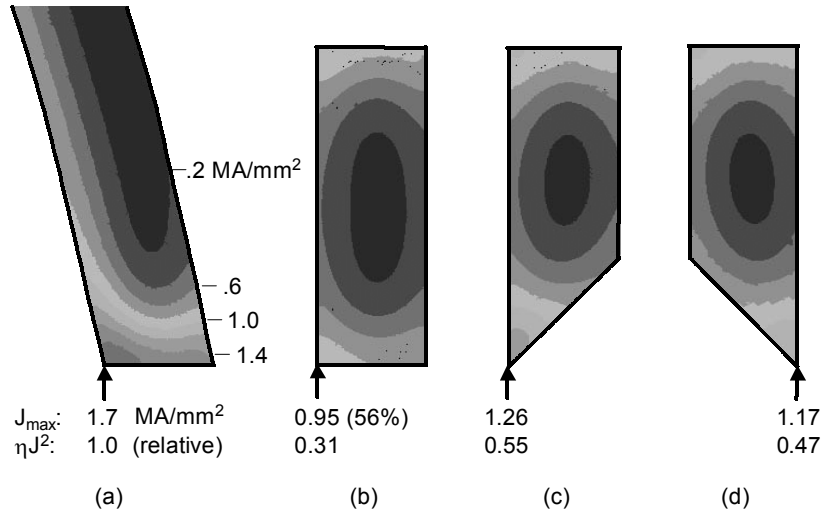| 16. SECURITY CLASSIFICATION OF:			17. LIMITATION OF ABSTRACT	18. NUMBER OF PAGES	19a. NAME OF RESPONSIBLE PERSON
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Figure 2. (a) Calculated current distribution in Z51 return conductor carrying 2 MA per rib. (b) Current distribution in Gamble II with 0.5 MA per rib, cross section with no bevel. (c) bevel in (d) bevel out.

(0.5 MA/rib) and the local ohmic heating rate (ηJ^2) relative to Z51, are indicated below the contour plots. For the cross section similar to Z51 (Fig. 2b), the maximum current density is 56% and the local heating is 31% of the Z51 values. The beveled cross sections result in significantly greater current density at the apex and might be expected to produce plasma sooner.

Plasmas in the slot region and the region between the rib and return conductor were probed with laser diagnostics. A pulsed nitrogen laser (500 ps, 200 μJ, 337 nm) was used to produce a 2D schlieren image at one moment in time. A high-sensitivity, two-color interferometer [2] recorded the time-dependent electron and neutral line-integrated densities at one location in the cross section. The schlieren timing and the interferometer beam location were varied shot-to-shot.

The schlieren diagnostic produces an image that indicates where the plasma density gradient is sufficient to refract the nitrogen laser beam out of a small aperture one focal length from an imaging lens. For the parameters of this experiment, the film is unexposed where $\overline{\nabla n} > 8 \times 10^{18}\, cm^{-4}$. Film exposure corresponds to regions with smaller density gradients. Assuming the density scale length, n/∇n ~ 0.1-1 mm, the corresponding electron density is $10^{17\text{-}18}$ cm^{-3}.

The two-color interferometer uses cw lasers with 0.5 and 1 μm wavelengths, aligned along the same line of sight parallel to and a known distance from the ribs. These scene beams are combined with reference beams to form an interference signal for each wavelength. The time-dependent, line-integrated electron and neutral densities are derived from the signals until refractive effects dominate.
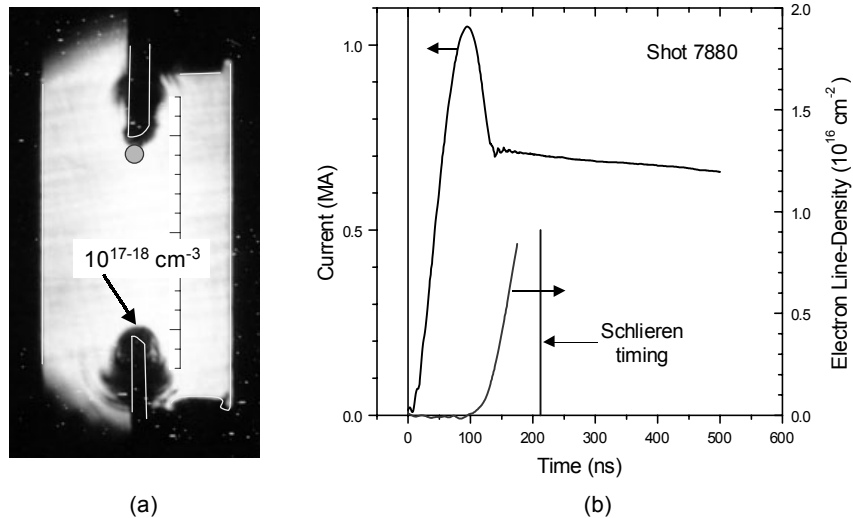

Figure 3. (a) Schlieren image for shot 7880 with "bevel-in" cross section, taken 212 ns after the start of the current. The upper rib is gold-coated, the lower rib is stainless steel, not cleaned prior to the shot. The scale tick marks are 1 mm apart and extend from the top to bottom edges of the 2-cm long ribs. (b) Electron density, current waveform and schlieren timing for shot 7880.
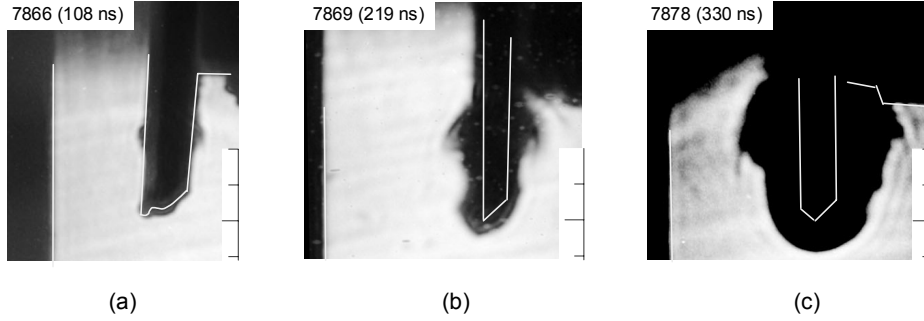
Figure 4. Schlieren images with bevel-in cross section: (a) 108 ns (b) 219 ns (c) 330 ns.

II. RESULTS

Example of data obtained on one Gamble II shot are shown in Fig. 3. Fig. 3a is a schlieren photograph with "bevel-in" ribs taken 212 ns after the start of the current. The upper rib is gold coated (as on Z51), the lower rib is "as-delivered" stainless steel. The planar return conductor is to the left of the ribs. White lines indicate the electrode boundaries, transferred from a shadow image taken prior to the shot. The boundary of the dark regions outside the electrodes corresponds to electron density greater than $10^{17\text{-}18}$ cm^{-3}. Plasma has expanded farther from the stainless rib than from the gold-coated rib.

Example data from the two-color interferometer are shown in Fig. 3b for the same shot. The laser beam location is indicated by the circle in Fig. 3a, centered 1 mm from the edge of the rib, in the slot. The Gamble II current waveform starts at t = 0 and increases to 1.05 MA in 100 ns, then decreases and crowbars at 0.7 MA because the insulator flashes. Plasma density is detected starting at t = 100 ns, increasing to 4×10^{15} cm^{-3} (averaged over the 2 cm path length) before the signals are corrupted by refraction. The electron density derived from both wavelengths agree, indicating the signals are dominated by free electrons and not neutrals at this location.

Schlieren images of the upper rib at three different times are shown in Fig. 4. Each shot used the bevel-in cross section with gold-coated stainless ribs. The high density plasma expands away from the ribs starting at about 100 ns (Fig. 4a), and by 300 ns (Fig 4c) it has expanded about 1 mm from the electrode corresponding to a plasma velocity of 0.5 cm/μs. The results with the other two cross sections are almost identical. The increased extent of the plasma generated from a stainless rib compared with a gold-coated rib (as indicated in Fig. 3a) disappears when the stainless rib is cleaned in acetone prior to a shot.

Plasma density measured with the interferometer 5 mm from the rib in the slot indicate insignificant difference due to cross section, consistent with the observations from schlieren images. Interferometer measurements in the slot at different distances from the rib are shown in Fig. 5. The inset illustrates the beam location relative to the rib. Low-density (10^{14} cm^{-3}) plasma appears at 1, 3 and 5 mm at about 100, 200 and 300 ns, respectively, corresponding to a velocity of 2 cm/μs. Refractive limits are less severe at greater distances allowing measurements for longer times and to greater densities.

Measurements at 1-2 mm from the rib toward the return conductor indicate a significant neutral component with density about ten times greater than the electron density (assuming the neutrals have the same refractive index as air). The velocity of the plasma/neutral mixture toward the planar return conductor is about 3 cm/μs.

III. CONCLUSIONS

Plasmas are generated in return current structures for parameters of the Z generator. Low density (10^{14} cm^{-3}) plasmas expand from the edges of return conductor ribs starting 100 ns after the start of the Gamble II current and expand into the slot at 2 cm/μs. Higher density ($> 10^{17\text{-}18}$ cm^{-3}) plasmas expand more slowly. Significant neutral density was observed in the area corresponding to the region between the return conductor and the wire array. Dirty rib surfaces result in qualitatively more plasma generation.
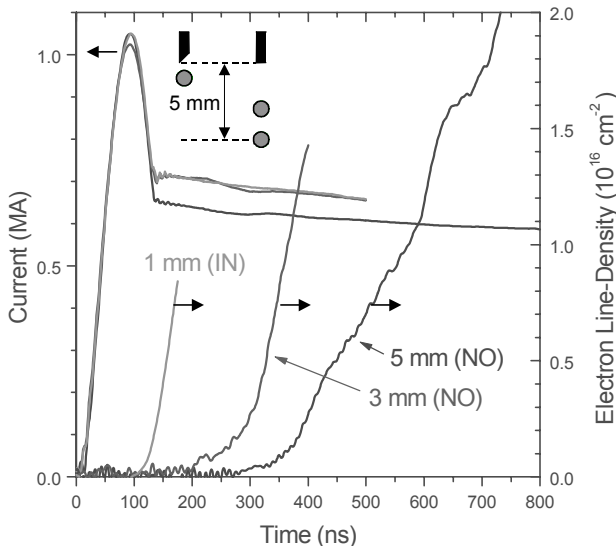

Figure 5. Electron-density measured 1, 3, and 5 mm from the rib in the slot.

For Z51 parameters, plasma generation probably occurs earlier than on Gamble II because the current density is about two times greater than that tested here. For a linear rising current, the same ohmic heating will occur in about 70 ns versus 100 ns on Gamble II. This plasma generation mechanism is not expected to negatively impact power flow or x-ray output for Z51 parameters, however, for configurations with smaller diameters the current densities can be greater, resulting in earlier plasma generation.

Future Gamble II experiments could include using pure metals (Cu or Al) to facilitate modeling, higher current densities (for example, using one rib), and in situ heating to expel impurity gases prior to the current pulse. Delaying these plasmas may be important for future experiments attempting to increase the power density at the load.

IV. ACKNOWLEDGEMENTS

IV. REFERENCES

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